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INITIAL FAA TESTS ON THE NAVIGATION SYSTEM USING TIME AND RANGING GLOBAL POSITIONING SYSTEM Z-SET

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July 1982

Interim Report

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U.S. Department of Transportation
Federal Aviation Administration
Systems Research & Development Service
Washington, D.C. 20590

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Technical Report Documentation Page

1. Report No. DOT/FAA/RD-82/8	2. Government Accession No. AD-A119 289	3. Recipient's Catalog No.
4. Title and Subtitle INITIAL FAA TESTS ON THE NAVIGATION SYSTEM USING TIME AND RANGING GLOBAL POSITIONING SYSTEM Z-SET		5. Report Date July 1982
		6. Performing Organization Code ACT-100
7. Author(s) Robert J. Esposito		8. Performing Organization Report No. DOT/FAA/CT-81/73
9. Performing Organization Name and Address Federal Aviation Administration Technical Center Atlantic City Airport, New Jersey 08405		10. Work Unit No. (TRAIS)
		11. Contract or Grant No. 049-330-110
12. Sponsoring Agency Name and Address U.S. Department of Transportation Federal Aviation Administration Systems Research and Development Service Washington, D.C. 20590		13. Type of Report and Period Covered Interim Report April through December 1980
		14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

The Federal Aviation Administration (FAA) received a Navigation System Using Time and Ranging (NAVSTAR) Global Positioning System (GPS) Z-set for independent test and evaluation after this receiver was acceptance tested aboard a United States Air Force C-141 aircraft over the Yuma Proving Ground instrumented range. This report describes the initial familiarization studies conducted by the FAA in a twin turboprop engine Grumman Gulfstream with the Z-set in a stand-alone configuration. The familiarization studies included satellite shielding tests, satellite acquisition/reacquisition tests, nonprecision approaches to five east coast airports, and operations in high noise/radiofrequency interference (RFI) environments (over airports, cities, and television towers).

17. Key Words	18. Distribution Statement
NAVSTAR-GPS Z-Set Receiver Global Positioning System RFI Tests	This document is available to the U.S. public through the National Technical Information Service, Springfield, Virginia 22161

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	15	

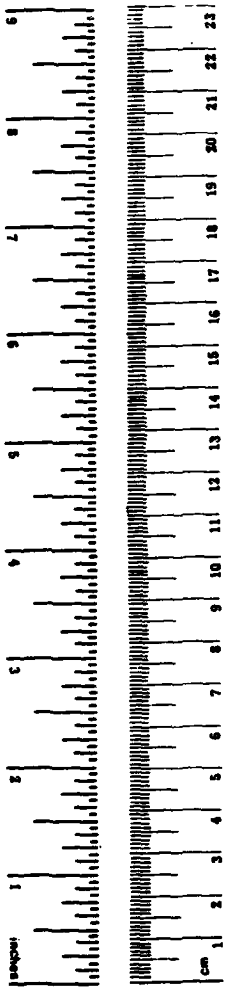
Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

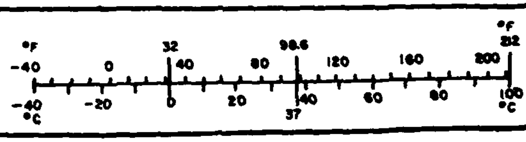
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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INTRODUCTION

The prototype Navigation System Using Time and Ranging (NAVSTAR) Global Positioning System (GPS) is under development by the Department of Defense (DOD) (reference 1). GPS will utilize a constellation of 18 satellites in 12-hour orbits to broadcast worldwide, real-time, precise position information on frequencies of 1227.60 and 1575.42 megahertz (MHz). The fully deployed system (1988 time frame) will permit suitably equipped users to determine position within 25 meters (2 distance root mean square (drms)) horizontal accuracy and within 30 meters (2 sigma) vertical accuracy (reference 2). (The 2 drms value refers to the probability that a circle of given radius will contain at least 95 percent of the data points.) The Federal Aviation Administration (FAA) is responsible for evaluating GPS as a potential navigation system for civil aviation operations.

In a previous report, the author described FAA acceptance tests on a NAVSTAR GPS Z-set receiver (reference 3). The tests were performed by the DOD over the instrumented range of the Yuma Proving Ground, Arizona, in an Air Force System Command (AFSC) C-141 aircraft with FAA observers aboard. The aircraft reference trajectory was determined by a laser tracker system and compared to a GPS receiver derived position. In addition, a fiducial receiver located on the Yuma range measured local position errors resulting from the space segment errors. The independent FAA findings on the acceptance tests (five flights and over 6 hours of test data) were in general agreement with previous DOD results (reference 4) and are summarized as follows:

1. The results indicated that the Z-set will meet FAA requirements for nonprecision approaches (100 meters, 2 drms accuracy in a horizontal plane) (reference 2) under specified conditions of aircraft flight dynamics, satellite accuracy, and satellite geometry, although the Yuma tracking system did not permit comprehensive testing on actual approaches.

2. The Z-set errors generally increased during turns; vertical errors were generally larger than horizontal errors.

3. The mean errors of the Z-set in the horizontal plane (averaged over nominal 1,400-second flight segments) compared favorably with those of more sophisticated airborne receivers and with the local errors recorded by the ground truth (fiducial) receiver at Yuma (typically to within 6 meters).

4. The main contribution to the averaged horizontal Z-set errors stemmed from the space segment, which had abnormally high errors during the Yuma tests, and not from the flight dynamics.

5. Averaged vertical errors for the Z-set did not generally correlate as well as the horizontal errors with other GPS receivers.

6. The Z-set did not "lose" a satellite during normal or expedited aircraft maneuvering and attitude conditions (including 180° turns) when the line-of-sight propagation link between the satellite and GPS antenna was briefly lost.

7. The Z-set, aided by a barometric altitude input, exhibited horizontal plane performance equivalent to four-satellite operation though navigating on three satellites.

The FAA received the same GPS Z-set receiver, serial number 6, for independent test and evaluation after the Yuma acceptance tests were completed. This report describes the initial familiarization and radiofrequency interference (RFI) tests conducted by the FAA in a twin turboprop engine Grumman Gulfstream aircraft. The purpose of these preliminary studies was to survey typical Z-set behavior and performance in an operational environment, especially during nonprecision approaches, prior to beginning a definitive test program. For the flight test results reported here, the set was operated in a stand-alone configuration and was not yet interfaced to an automated data collection system.

TEST CONFIGURATION

Z-SET RECEIVER.

The Magnavox Z-set is a single channel receiver which sequentially processes coarse acquisition (C/A) signals on 1575.42 MHz from four satellites. It was designed as a relatively low cost, low dynamics, but fairly sophisticated first generation navigator for transport aircraft. The Z-set consists of the antenna assembly, low noise preamplifier, receiver/processor, and control/display unit (CDU). Its main features are given in table 1. Only one parameter (one line) is displayed at a time, but all of the CDU display parameters for a given time can be stored by activating the freeze button. The Z-set can accommodate only two-dimensional (horizontal) waypoints.

The FAA tests reported here were performed on Z-set serial number 6 with software version number 9. The resident 8-state Kalman filter computes user position, velocity, time error, and frequency error usually every 1.2 seconds (the normal sequence time per satellite). The CDU position display is updated every second based on the last navigation solution for aircraft speed and ground track (both held constant).

The Z-set periodically reviews the currency of the satellite almanac data and the selection criteria for the optimum satellite constellation while maintaining four-satellite track. The latter algorithm is based on weights from the geometric dilution of precision (GDOP) value, satellite health status, tracking and data gathering history, and satellite visibility period. The Z-set is programmed to begin/end satellite tracking at a minimum elevation angle between 10° and 15° above the horizon. If the set decides to select another satellite constellation, it will automatically drop one satellite and attempt to acquire its replacement while navigating on three satellites.

Z-set number 6 has an interface module which inputs encoded barometric altimeter data (increments of 100 feet/30.5 meters) into the navigation solution during periods of two- or three-satellite tracking. Software version number 9 (updated by version 10) had DOD discrepancy reports concerning the altitude hold function under three-satellite navigation and the acquisition/reacquisition function for the third and fourth satellites. The latter problem may have been caused in part by out-of-specification drifts in the quartz oscillator circuits in NAVSTAR vehicles 1 and 2.

TABLE 1. Z-SET PARAMETERS

Operational Parameters	Characteristics
RF signal input level (to antenna)	-130 to -120 dBm
Frequency (L_1)	1575.42 ±10 MHz
Polarization	Right hand circularly polarized
Antenna gain	0 dBIc minimum from 30° to 90° (above the horizon) -1.5 dBIc minimum from 5° to 30°
Antenna coverage	Hemispherical
Antenna axial ratio	< 3 dB at 90° < 5 dB at 45° < 16 dB at 5°
Pseudorange measurement accuracy	≤ 50 meters (2 sigma)
Vehicle velocity dynamics	≤ 400 meters per second (m/s)
Vehicle acceleration dynamics	≤ 5 m/s^2
Initial signal acquisition time	< 300 seconds
Jamming to signal power ratio	25 dB
Preamplifier bandwidth selectivity at L_1	24 ±8 MHz at 3 dB point ≤ 50 MHz at 70 dB point
Preamplifier gain at L_1	30 to 39 dB

Displayed Parameters	Characteristics
Test	Checks light emitting diode (LED) operation
Estimated position error	Calculated from the Kalman filter covariance matrix, resolution to 0.01 nautical mile (nmi)
Distance to waypoint	Resolution to 0.1 nmi
Bearing to waypoint	Resolution to 0.1°
Latitude	Resolution to 1 arc second
Longitude	Resolution to 1 arc second
Altitude	Resolution to 1 foot
Waypoint magnetic variation	Resolution to 0.1°
Ground speed	Resolution to 1 knot
True ground track	Resolution to 0.1°
Day/time	GPS epoch time to 1 second
Unmarked, 6 o'clock position	Fault messages and satellite data

SPACE SEGMENT.

NAVSTAR vehicles 1 through 6 were used during various portions of the FAA tests. Flight tests were conducted during visibility periods with three to six satellites having different ages of ephemeris update. The atomic clocks in NAVSTAR 1 and 2 suffered previous failures; these satellites were operating on quartz oscillators which resulted in large navigation errors. Upon request from the FAA, NAVSTAR 1 and 2 were placed in an unhealthy status (and thus eliminated from the Z-set navigation solution) by the GPS space segment control station at Vandenberg Air Force Base.

GDOP information, which is dependent upon the satellite constellation, is presented when known. (The Z-set CDU does not display satellite identities currently contributing acceptable navigation data and from which ephemeris data have been collected.) Local position errors determined by the fiducial receiver at the Yuma Proving Ground (depending upon the Yuma GDOP figure and, hence, the satellites being tracked) are given as a guideline to space segment errors. The FAA tests were performed over the east coast of the United States, approximately 2,000 miles away from Yuma.

TEST CONDITIONS.

All tests were conducted in an FAA Grumman Gulfstream, model G-159, which is a corporate-type aircraft with twin turboprop engines, low wing, and conventional tail (see figure 1). The conical spiral GPS antenna was mounted on top of the fuselage, slightly behind the leading edge of the wing. The aircraft was crewed by FAA pilots and project personnel.

All flights were performed under visual flight conditions, at most times under instrument flight rules (IFR). Only the project engineer operated the Z-set; the pilots did not use it to navigate. Z-set results were recorded by hand or a voice recorder, usually after storing the display parameters. A number of familiarization tests were performed:

1. Turns while tracking three satellites with one satellite at a low elevation angle.

2. Approaches with four or more satellites in view.

3. Airborne reacquisition attempts.

4. RFI studies in an airport environment, over urban areas, and in the vicinity of radio and television towers.

All aircraft turns (30° through 180°) were made at bank angles less than 30° unless specified otherwise.

APPROACH PROCEDURES.

In order to simulate nonprecision approaches, actual visual missed approaches were made to a number of east coast airports. When the copilot visually judged passage of the runway threshold, he signaled the project engineer who immediately activated the freeze/store command in the Z-set. At threshold, the aircraft was flying at approximately 130 knots and 100 feet above ground level.

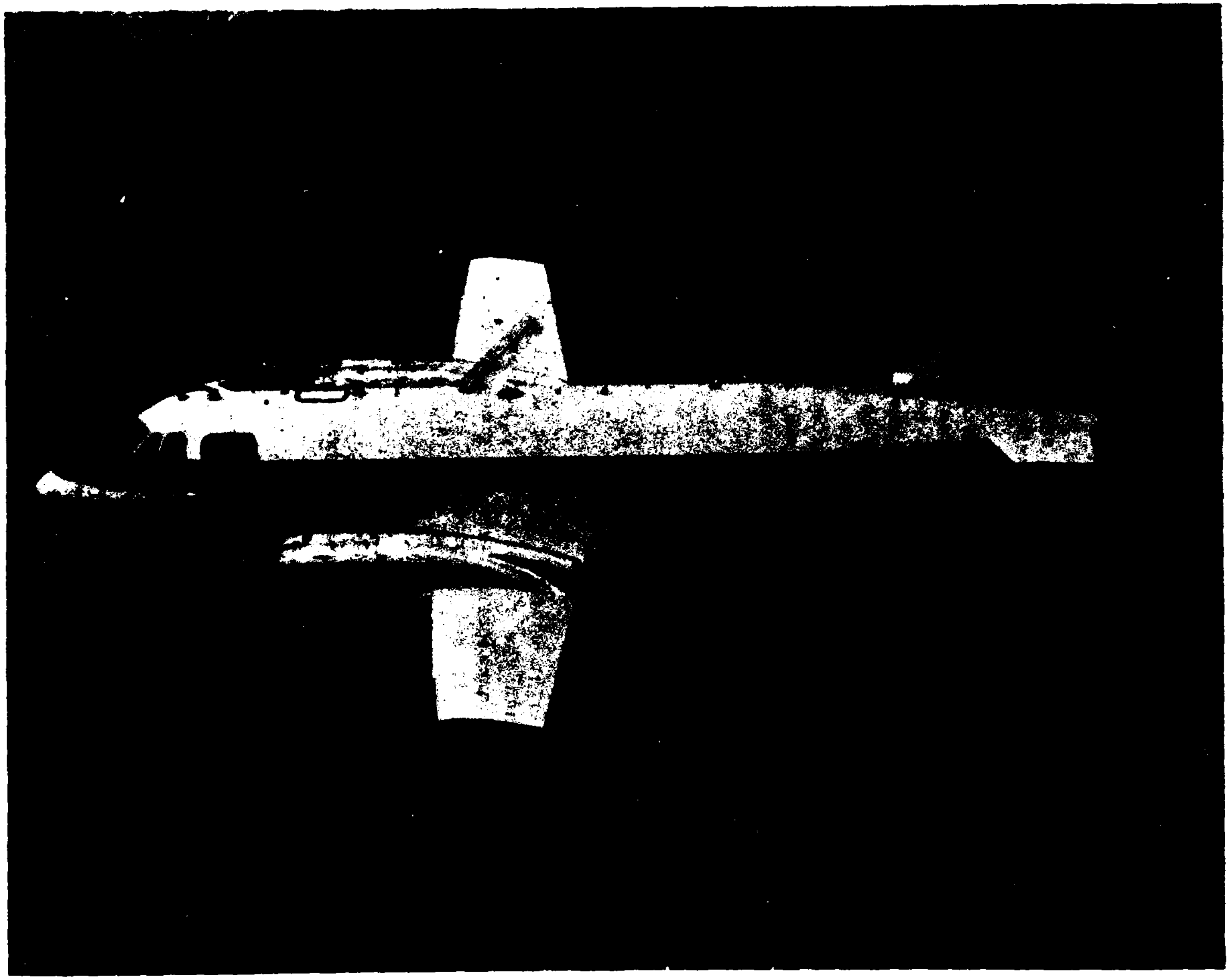

FIGURE 1. GRUMMAN G-159 AIRCRAFT (N-47) WITH Z-SET ANTENNA (MICROWAVE SPECIALTIES CORPORATION MODEL 1133)

In the post-flight analysis, the receiver computations for latitude, longitude, and track (aircraft trajectory) were compared to threshold coordinates (surveyed points) and runway direction. The position difference between the Z-set derived solution and threshold coordinates is defined as the GPS receiver position error, which includes the human factors errors in threshold location and reaction times. The position error was then calculated in terms of along-track and crosstrack errors in order to determine whether the Z-set and GPS would meet minimum FAA requirements for nonprecision approaches (100 meters, 2 drms accuracy in the horizontal plane).

Since the Z-set CDU updates its position every second, the aircraft probable position error in the longitudinal direction can be as large as 67 meters if copilot and operator errors are ignored and the aircraft is flying a constant trajectory. Also, the Z-set CDU displays latitude to 1-arc second (30.9 meters), longitude to 1-arc second (23.8 meters at the test sites), and ground track to 0.1°. Typically, experienced pilots making approaches will have aligned the aircraft at threshold to within 6 meters of the runway centerline and the aircraft track to within 2° of the runway direction. It is assumed that the pilots attained these goals on all approaches.

RESULTS

SATELLITE SHIELDING TESTS.

It was decided to determine first whether the Z-set would maintain satellite lock during turns on approaches when the relative angle between the satellite and GPS antenna was below 5°. The antenna parameters are given in table 1. The secondary pass of NAVSTAR vehicles 2, 3, and 6 provided an appropriate three-satellite constellation over the FAA Technical Center, Atlantic City Airport (ACY), New Jersey. The maximum elevation angle of NAVSTAR 3 during this pass was 26° above the horizon. During the test periods, the crystal clock in NAVSTAR 2 was exhibiting erratic frequency drifts, thereby, significantly degrading the navigation solution. Also, the satellite ephemeris data were at least 8 hours old.

Five missed approaches to ACY were flown in a sequential, right-hand cloverleaf pattern to runways 22, 13, 04, and 31. Note that runway 13/31 is perpendicular to 04/22. A similar second flight of nine approaches was made using a left-hand cloverleaf pattern. The bank angles for most turns were from 20° to 30°, although some reached 45°. The Z-set navigated via the three visible satellites plus barometric altitude throughout both flights until NAVSTAR 3 fell below an elevation angle of 15°. These tests confirmed the previous Yuma results that the Z-set does not indicate satellite track loss during normal or expedited turns and maneuvers when the line-of-sight RF propagation link is briefly masked due to aircraft attitude. The erroneous navigation signals from NAVSTAR 2 resulted in position errors of approximately 0.6 nautical mile (nmi) at threshold.

APPROACH RESULTS.

In the next series of tests, a total of 38 approaches were made in six separate flights to five different airports when four to six satellites were available for navigation. NAVSTAR 2 was used only for the first mission. The other satellites

were uploaded by the space control station with new ephemeris data shortly before the flight began. However, additional uploads sometimes occurred during the test flights.

In the first flight, 13 left-hand approaches were made to ACY, most of which were in a cloverleaf pattern. The bank angle during turns did not exceed 30°. The Z-set was not able to maintain continuous track of four satellites during this mission. It periodically dropped a satellite and, after several minutes, returned to four-satellite navigation. At this time, NAVSTAR 1, 3, 4, 5, and 6 were visible. We are unable to determine GDOP versus time since we do not know which satellites were being tracked. Late in the mission, the Z-set dropped two satellites when NAVSTAR 4 was setting and NAVSTAR 2 was rising. Both satellites were at elevation angles between 15° and 20° above the horizon at this time. Also, the other satellites were still visible and their GDOP figure was relatively large (approximately equal to 10). The receiver difficulties were probably caused by the following, in some cases separately and in other cases collectively: (1) large clock drifts in NAVSTAR 2 and possibly in NAVSTAR 1; (2) satellite acquisition/reacquisition attempts and failures for the optimum satellite constellation; and (3) satellite ephemeris changes during the mission.

Ground truth receiver data from Yuma were not available.

The second mission consisted of eight approaches to ACY in a right-hand cloverleaf pattern. NAVSTAR 2 was placed in an unhealthy status by the space control station. The Z-set navigated on four satellites throughout the mission. The fiducial receiver at Yuma showed that NAVSTAR 1 exhibited a ranging error of approximately 12 meters near mission conclusion; errors from the other satellites were smaller.

For both ACY flights, the maximum absolute Z-set errors, when the receiver was navigating on either three satellites (5 approaches) or four satellites (13 approaches), were 77 meters along-track, 27 meters crosstrack, and 1.2° track angle. The three approaches in the two-satellite navigation mode were made consecutively over a 10-minute period and gave an indication of Z-set clock degradation and performance in a terminal environment. The maximum absolute errors were 123 meters along-track, 92 meters crosstrack, and 1.2° track angle.

Details of the other four flight were: four approaches to John F. Kennedy International Airport (JFK), four approaches to Philadelphia International Airport (PHL), four approaches to Logan International Airport (BOS), and three approaches to Baltimore-Washington International Airport (BWI), respectively. One landing approach each to ACY was made at the conclusion of the JFK and PHL missions. The Z-set maintained four-satellite lock on the four flights. NAVSTAR 1 was placed in an unhealthy status, and the navigation signals from NAVSTAR 2 had already been turned off due to clock problems.

The GPS errors for the JFK, BOS, and BWI missions were equal to or less than those observed for the ACY approaches (three- or four-satellite navigation) previously discussed in this test series. Ground track errors were not recorded in the JFK mission. The airport GDOP values varied from approximately 5.5 to 8.5. The Yuma ground truth receiver reported local three-dimensional position errors of less than 15 meters (GDOP <7.5).

In the PHL mission, the GPS position errors were larger than the other five flights when the Z-set was navigating on either three or four satellites. The along-track error ranged from -121 meters (PHL, GDOP$\simeq$6) to +152 meters (ACY, GDOP $\simeq$13). The maximum absolute errors were 43 meters crosstrack (PHL) and 1.5° ground track angle (PHL). The Z-set ground track was not recorded on the landing approach at ACY. The fiducial receiver data were available for only the first half of the mission, and the Yuma local position error was under 15 meters (GDOP <8). Although the PHL-ACY GDOP figure increased from approximately 5.5 to 13 during the flight, we believe that the crew observation/response errors contributed significantly to the along-track error.

The mean GPS errors for 35 approaches (three- or four-satellite navigation) are 0.5 meters along-track and 4.8 meters crosstrack, the corresponding standard deviations are 56.6 and 17.2 meters, and the corresponding rms errors are 55.8 and 17.6 meters, respectively. The along-track and crosstrack errors contain the directional components of the CDU resolution uncertainty (1-arc second or 30.9 meters). The CDU update rate (67-meter uncertainty) and the crew human factors effects contribute primarily to the along-track error. (Recall that the maximum absolute ground track error is 1.5°, and the CDU update and human factors contributions to the crosstrack errors are small.)

The along-track standard deviation as given is too large to meet the 100 meter 2 drms accuracy requirement for nonprecision approaches. On the other hand, the crosstrack standard deviation may be underestimated due to the 30.9 meter resolution limit of the CDU (1 sigma resolution error of 8.9 meters) and the limited sample size. An error budget analysis of the test configuration and results is presented which should provide a fairly realistic representation of the true performance of the Z-set receiver.

We assume that the observed crosstrack errors are random samples from a normal distribution. At the 95 percent confidence interval, the crosstrack standard deviation lies between 14.0 and 23.1 meters and its mean error between -1.1 and +10.7 meters. A more conservative upper bound is obtained by setting the crosstrack standard deviation equal to 30.5 meters; i.e., it is overestimated by raising it to the approximate uncertainty of the CDU measurement. Although a GPS bias error of ±10 meters is not an unexpected event for a given satellite constellation on a given day, we set the mean error equal to zero. This value not only simplifies our later computations for the circular error probability, but also does not significantly change the error probability results. Then, the probability (single dimension) that the crosstrack error with a zero mean and 30.5 meter standard deviation lies within ±100 meters is approximately 99.9 percent. (The corresponding probability for a 10-meter mean error is approximately 99.7 percent.)

Let us next assume that the upper bound on the along-track standard deviation, after the receiver update and human factor contributions are removed, is also 30.5 meters. Our reasons for doing so are:

1. The observed crosstrack standard deviation lies within the basic measurement uncertainity.

2. The crosstrack and along-track errors should be approximately equal since the approaches were made to several runways at different airports under varying space segment conditions and the crosstrack errors were independent of runway direction (perpendicular runways at ACY).

We further stipulate that:

1. The along-track errors are random, normally distributed and uncorrelated to the crosstrack errors.

2. The mean along-track error is zero.

3. The bivariate normal distribution provides a reasonable estimate for computing the circular error probability.

Then, the probability that the GPS Z-set along-track and crosstrack errors fall inside a circle of a 100-meter radius is approximately 99.5 percent. The 2 drms value is 86.0 meters (98.2 percent probability for this case) and is a conservative upper bound on the 95 percent probability circle. Furthermore, 95 percent of error points fall within a circle of approximately 74.7-meter radius, or the receiver would meet FAA requirements for a bias error of approximately 25 meters in the horizontal plane. If the standard deviations are arbitrarily increased, the bivariate normal distribution for zero mean values predicts that the 100-meter 2 drms accuracy requirement is satisfied for along-track and crosstrack standard deviations of 40.8 meters (which would certainly be detected in crosstrack measurements).

Based on this analysis of the familiarization test data, we conclude that the altitude-aided Z-set and an appropriate three- or four-satellite constellation will meet FAA requirements for nonprecision approaches. Our findings are in agreement with the previous FAA acceptance tests and DOD results on the Z-set. In the next phase of testing, the FAA will evaluate the Z-set and GPS performance during approaches using an airborne data collection system, a time-synchronized tracking system, and a ground-based fiducial receiver.

If the PHL mission results are not included, the along-track and crosstrack mean errors for 30 approaches are 9.0 and 1.6 meters; the corresponding standard deviations are 37.8 and 15.4 meters; and the corresponding rms errors are 38.4 and 15.2 meters, respectively. From the previous computations and discussion, these values yield an accuracy which meets FAA requirements. For example, the circular error probability (100-meter radius) is approximately 98.3 percent when (a) the mean values are assumed to be zero, (b) the crosstrack standard deviation is raised to 30.5 meters, and (c) the other assumptions hold.

RFI TESTS.

RFI measurements in the L_1 band were taken at several airports, on some of the approach missions, and at low altitude over the surrounding urban, rural, and/or water areas including high power radio and television (TV) transmitters. A portion of the RF power from the Z-set preamplifier was coupled to a Tektronix model 7L13 spectrum analyzer, and the emission spectrum in the vicinity of frequency L_1 was observed on a cathode ray tube (CRT) display with the Z-set operating. The preamplifier parameters are given in table 1.

With the following exception, the main L_1 band emissions were intermittent pulses to -60 decibels above 1 milliwatt (dBm) or higher peak power levels (measured at the front end of the Z-set receiver/processor) from aircraft and airport equipment. Our analysis of the preliminary test data indicates that spurious radiation from

other aircraft distance measuring equipment (DME) is the most likely candidate. However, the DME on the Gulfstream caused approximately -70 dBm intermittent pulses in the L_1 band. The results of the approach tests already demonstrate that the Z-set can navigate accurately in the vicinity of high activity, fully instrumented airports. Laboratory tests show that an RF continuous wave (CW) signal of approximately -30 dBm in the L_1 band inputted to the receiver/processor (or a signal of approximately -60 to -70 dBm inputted to the preamplifier) caused the Z-set to lose satellite lock.

The main potential interference signals are radiated by high power ultra high frequency (UHF) TV transmitters (maximum allowed output of 5 megawatts), whose harmonics and spurious radiation (60 to 80 dB or more below the fundamental) lie within the bandpass of the Z-set preamplifier. The third harmonic from station WNJS, channel 23 (frequency assignment 524-530 MHz), served as a convenient example. WNJS operates with 809 kilowatts (effective radiated power) visual power, 125 kilowatts aural power, and smaller amount in the chrominance subcarrier. Its 1,047 foot (above ground level) tower is located approximately 5 miles from the Hammonton Municipal Airport (N81), New Jersey.

The Grumman G-159 flew in the vicinity of the WNJS tower: (a) to within 500 feet directly overhead, (b) to within 0.5 nmi in the horizontal direction at an altitude 200 feet below the top of the tower, and (c) approaches to N81. The TV interference in the L_1 band became readily apparent on the CRT of the spectrum analyzer when the aircraft was approximately 1 nmi from the tower. The third harmonic emissions (maximum of -65 dBm) and high density noise pulses (peak power greater than -60 dBm) were most pronounced for case (b). In all cases, the Z-set continued to navigate without any noticeable effect from the radiated power. Although the initial RFI tests are promising, further investigation is warranted.

SATELLITE ACQUISITION STUDIES.

The Z-set frequently exhibited considerable difficulty in acquiring visible satellites as a prelude to collecting an almanac or to entering the navigation mode; i.e., after a search period the set would automatically return to the initialization mode. Acquisition attempts repeatedly failed, and it sometimes took 15 to 30 minutes before a satellite was acquired. (One of the DOD discrepancy reports for software version 9 dealt with the acquisition of additional satellite(s) when the set was already in a navigation mode.) All tests were done in flight or at an airport; the latter normally has a high noise background. On other occasions, the set successfully accomplished an airborne four-satellite acquisition within a few minutes of the first attempt.

The acquisition problem was initially thought to be partially caused by the out-of-tolerance drift in the clocks of NAVSTAR's 1 and 2, and, thus, an unreported consequence of the DOD discrepancy report. However, the same behavior was also observed when only NAVSTAR 3 through 6 were in a healthy status. The problem has persisted with the updated software version 10, which was written to correct the previous DOD discrepancy reports. It is planned to study the satellite acquisition process further when the Z-set is fully instrumented to the FAA data collection system, which will record relevant receiver events and RFI effects.

SUMMARY AND CONCLUSIONS

The Federal Aviation Administration (FAA) performed initial familiarization tests on a Navigation System Using Time and Ranging (NAVSTAR) Global Positioning System (GPS) Z-set receiver with software version 9 in a Grumman G-159 aircraft. The objective of the tests was to survey Z-set performance/capabilities in a stand-alone configuration before beginning a definitive, independent test and evaluation program on GPS applications for civil aviation. Our findings are in general agreement with previously reported FAA acceptance tests and DOD results.

A total of 35 visual approaches was made to five east coast airports with the Z-set using either three satellites plus barometric altitude or four satellites to navigate, and the GPS error was computed. The GPS error is defined as the difference between the Z-set receiver determined position and the runway threshold coordinates. The aircraft position over threshold was estimated by the copilot. The measured root mean square (rms) errors for the approaches were 55.8 meters along-track and 17.6 meters crosstrack, which included receiver, space segment, control/display unit (CDU) resolution, CDU update, and human factor errors.

Our error budget analysis of the data indicates that Z-set rms errors on non-precision approaches are actually 30.5 meters or less in along-track and cross-track, which yield a 95 percent probability circle with a radius of 74.7 meters. The GDOP value for these missions was typically less than 8.5, and the bias errors were small (less than 15 meters in three dimensions). The receiver successfully maintained satellite lock during turns when the radiofrequency (RF) propagation link between the GPS antenna and a satellite (at a low elevation angle) was briefly masked. In addition, the Z-set appeared to navigate accurately in the presence of high RFI/noise emissions from aircraft, airports, urban areas, and ultra-high frequency (UHF) television (TV) towers. Based on these preliminary test results, we conclude that the Z-set will meet FAA accuracy requirements for nonprecision approaches (100 meters, 2 drms accuracy in the horizontal plane) under appropriate satellite conditions.

The familiarization tests also showed that the Z-set, on occasion, experienced difficulties in acquiring: (a) a third or fourth visible satellite when one is falling to the horizon (reportedly corrected by version 10 software), and (b) an initial satellite in order to collect an almanac or to begin the navigation process. The cause of the latter problem remains unresolved and will be further investigated along with the other preliminary observations when the Z-set is interfaced to an automated data collection.

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